

Simulation of PBL Cloud Fields with Interactive Multi-Dimensional Longwave Radiative Forcing

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Motivation

Current models that simulate atmospheric flow typically use one-dimensional (1D) radiative transfer (RT) schemes. While presumably adequate for plane-parallel cloud geometries, multi-dimensional radiative transfer (MDRT) provides a more accurate treatment of RT for complicated cloud geometries. Our aim is to explore whether using MDRT affects cloud properties and evolution relative to a 1D treatment of RT (independent pixel approximation [IPA]). To explore the evolutionary nature of this radiative-dynamic interaction, we have coupled to a large-eddy simulation (LES) model the MDRT scheme of Evans (1998; Spherical Harmonics Discrete Ordinate Method [SHDOM]).

Analysis has at the present been restricted to longwave (LW) forcing of boundary layer stratocumulus. Stratocumulus clouds in the LW likely do not exhibit as much quantitative three-dimensional (3D)-IPA difference relative to a trade cumulus cloud field in the shortwave (SW), for example, but since they are predominantly radiatively forced, the dynamic feedback might be more pronounced.

Experiment Description

The Cooperative Institute for Mesoscale Meteorological Studies LES model was configured in a two-dimensional (2D) geometry (500×51). Initial conditions for the LES are derived from the Atlantic Stratocumulus Transition (ASTEX) A209 case simulated by Khairoutdinov and Kogan (1999), and a low initial cloud condensation nuclei concentration of 41 cm^{-3} is consistent with strong drizzle and cloud breakup.

The LES is coupled interactively to SHDOM. The LES supplies the liquid water content (LWC) field the radiative transfer package, which calculates the cloud optical properties and uses a correlated k-distribution to compute RT in 12 LW bands. Cloud droplet radius is based on a concentration of 50 cm^{-3} . The heating rates are then used to force the LES.

Reasons of computational expense dictate that the interactive case be 2D. The model is run for an hour using its own (1D) RT scheme to establish a reasonable boundary layer structure. Then, the simulation is forced using heating rates from SHDOM. The RT calculation is performed every 10 timesteps.

Prior coupled LES-SHDOM simulations compared MDRT and the IPA option in SHDOM, but a bias in downwelling IR above the PBL produced an artificial offset in cloud top heating rate. Instead of using the IPA option in SHDOM for our IPA (1D) test, we subtracted the horizontal radiative flux convergence from the MDRT, which for our 2D simulation was

$$\text{HR}_{\text{IPA}} = \text{HR}_{\text{MD}} - \left(\frac{-1}{\rho c_p} \frac{\partial F_x}{\partial x} \right)$$

Evolution of Statistics

The evolution of typical domain-mean statistics is shown in Figure 1. Differences between MD and IPA experiments do develop but do not appear to exhibit a systematic bias in this relatively short (5 h) simulation. Cloud base (updraft and downdraft) differs somewhat in the two cases, but that may be an artifact of the limited number of realizations (drizzle cells) over the domain.

Evolution of Cloud System Features

Figure 2 compares the cloud fields at the beginning of the interactive RT calculation (1 h) and then at hourly intervals from 3-6 h over a 10 km subset (20%) of the domain. Corresponding features in each cloud field are apparent early in the simulation, but by 6 h very little similarity remains. The effect of the horizontal flux divergence (heating rate) has brought about differences in the evolution of particular drizzle cell elements.

Figure 3 shows the time evolution of cloud fraction profiles for the MDRT and IPA simulations. Despite the drastic differences in cloud element evolution illustrated in Figure 2, very little change is visible in one measure of macroscopic cloud properties—cloud fraction. In fact, the very slight reduction of cloud fraction in the IPA simulation actually seems to be opposite the sense that the MD cooling rates would imply, since the lateral cloud cooling rates near cloud top should enhance negative buoyancy there and contribute to cloud breakup.

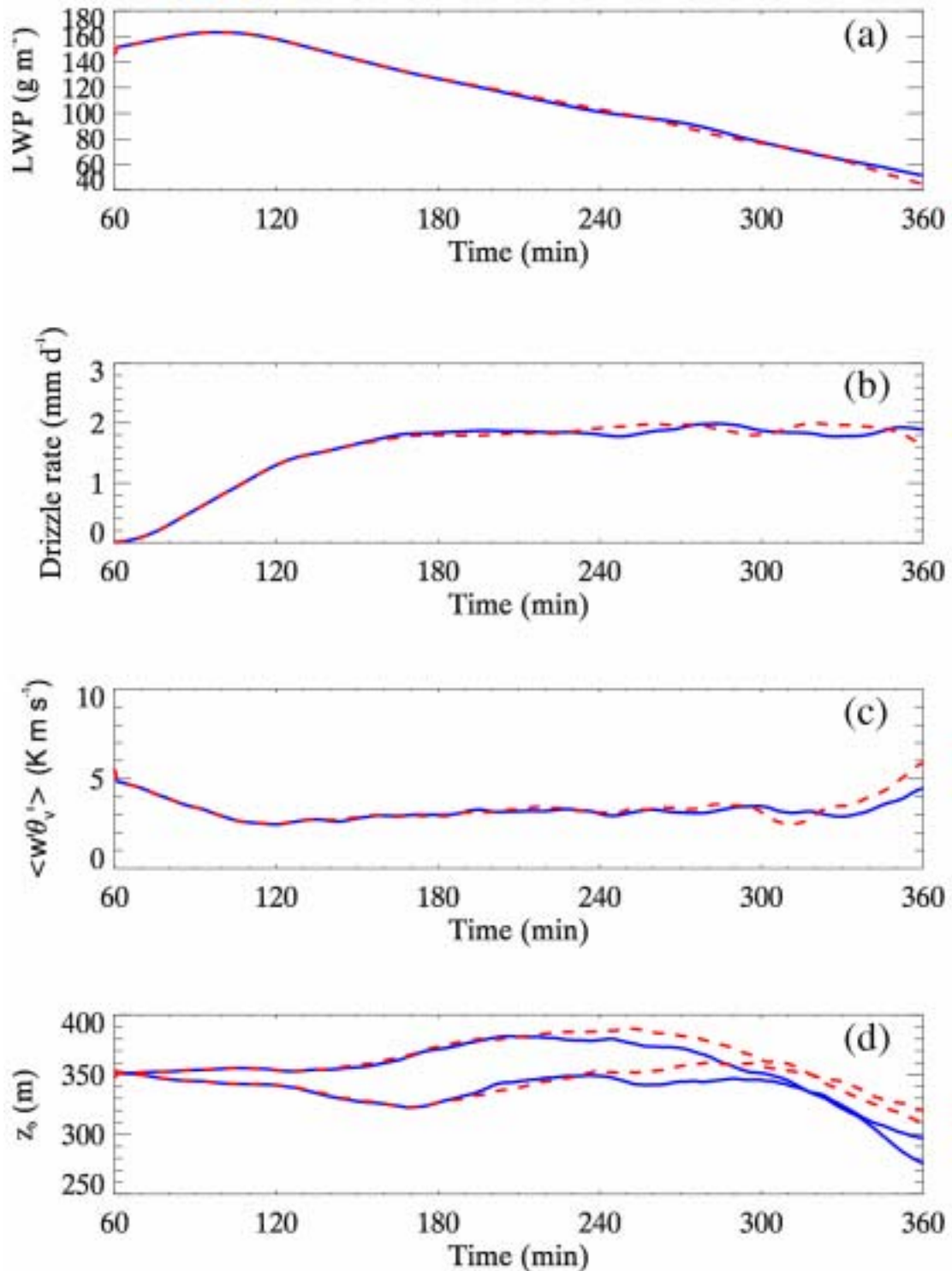


Figure 1. Time-series of various mean LES quantities from 1-6 h comparing the MDRT (blue, solid) and the IPA (red dashed) simulations. (a) LWP (g m^{-2}). (b) Surface drizzle rate (mm d^{-1}). (c) Buoyancy flux (K m s^{-1}). (d) Updraft and downdraft cloud base height (m). Updraft cloud base is lower relative to downdraft cloud base.

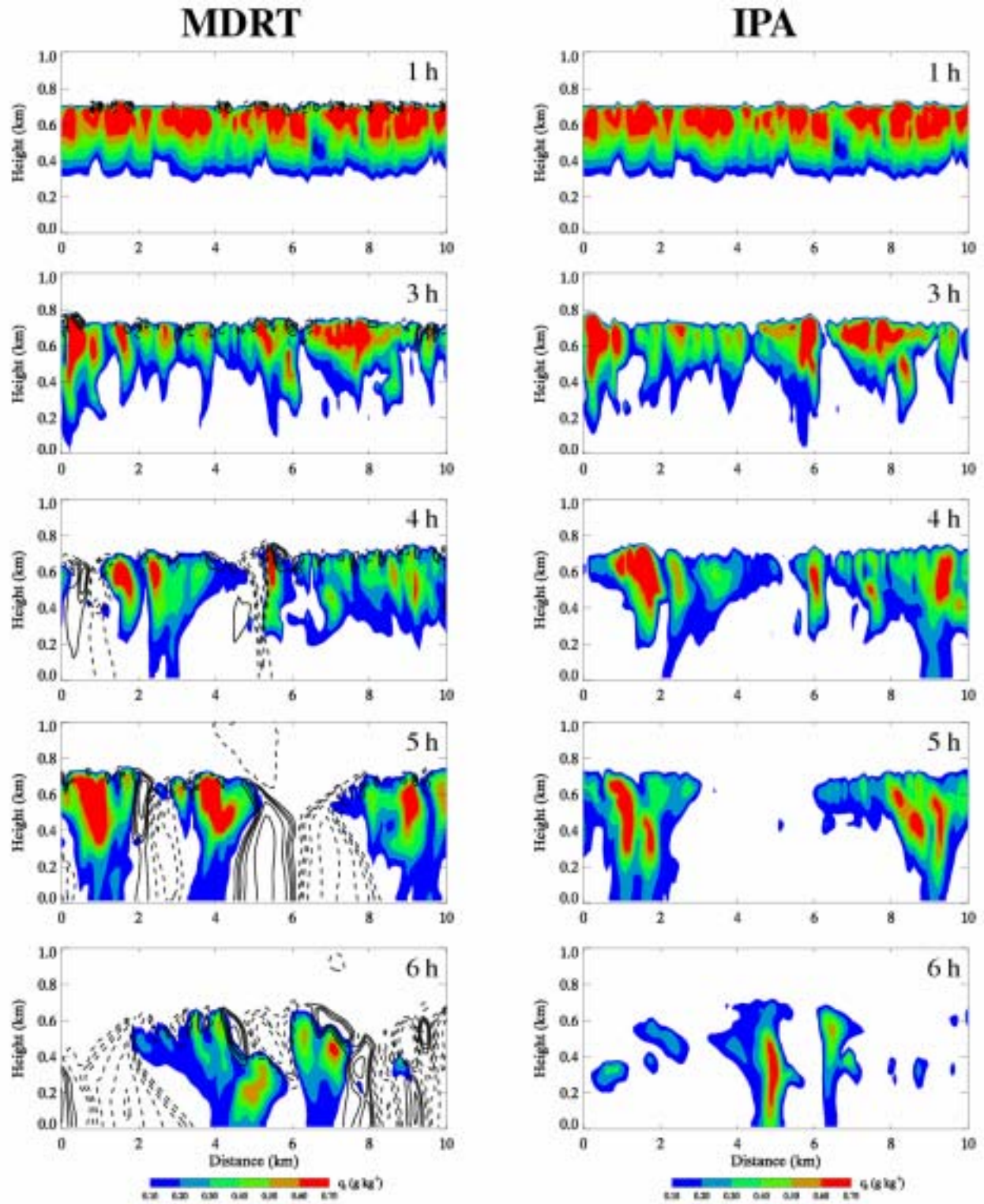


Figure 2. Liquid water mixing ratio (g kg^{-1}) and contours of horizontal radiative flux ($\pm 1, \pm 2, \pm 3, \pm 5, \pm 10, \pm 15 \text{ W m}^{-2}$) (for the MDRT simulation) over the same 10 km subregion of the model domain for MDRT and IPA simulations.

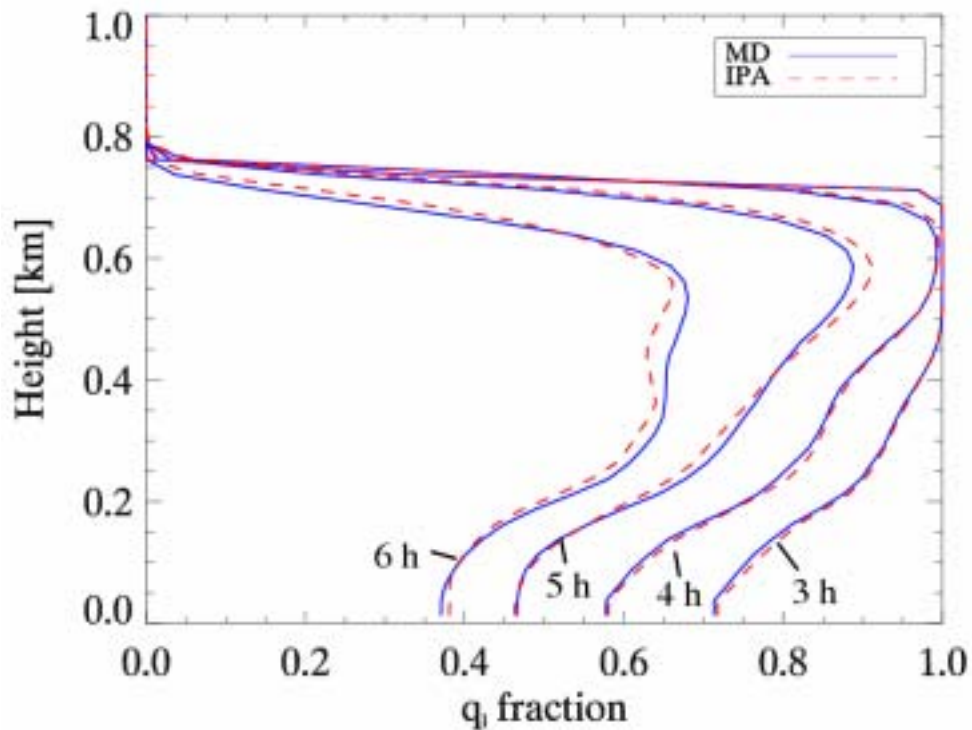


Figure 3. Hourly-mean cloud fraction profiles for MDRT and IPA simulations.

Conclusions

- The cross sections show that early on, the only significant horizontal fluxes are associated with the undulating cloud top.
- When the cloud field begins to break up, horizontal fluxes become more pronounced.
- Even for the “window” band shown (centered at $11\ \mu\text{m}$), there is a small amount of horizontal flux convergence in the clear regions between clouds.
- Early in the simulations, it is easy to find common cloud features in the two experiments, but it becomes more difficult as time progresses.
- The MDRT case exhibits slightly greater cloud fraction relative to the IPA simulation at 6 h, but we suspect the statistical validity of this result.

Future explorations under consideration:

- Longer time integrations (~ 12 h)
- Finer horizontal and vertical grid spacing
- BOMEX trade cumulus case

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